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RAPID PUBLICATION

Defect Imaging from a Remote Distance by Using Scanning Laser Source Technique with Acoustic Microphones

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Images of defects in plate-like structures can be generated using the scanning laser source (SLS) technique. When a laser Doppler vibrometer (LDV) is used as a receiving device in the SLS technique, images of defects can be obtained through measurements conducted from a distance. Because an LDV cannot receive vibrations reflected from outdoor structures that may have rough surfaces and large fluctuations in a stable manner, this paper discusses an imaging technique using a SLS with acoustic microphones as a receiving device. The results of the experiments that were conducted using various distances between the test plate and microphone showed that the quality of the defect images gradually degraded because of the attenuation of sound in air as the distance increased. Moreover, when the laser beam was reflected back to the microphone after scattering over the plate surface, the laser beam directly generated signals in the microphone due to the photovoltaic effect or alternating heat, preventing the acquisition of defect images. Thereafter, in order to establish remote defect imaging, an acoustic transmitter was connected to the microphone unit. Most of the experimental equipment were located at a remote distance except for the small microphone unit and transmitter. The experimental system enabled the generation of images of the defect in the test plate located at distances of 4 and 6 m. [doi:10.2320/matertrans.M2017326]

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1. Introduction

Many existing large structures such as bridges, tanks, and pipes require appropriate maintenance and periodical inspection. Therefore, the quantitative evaluation of defects in plate-like structures is of increasing importance[1–3]. Ultrasonic inspection is widely used in various inspection sites because it is a nonhazardous and reliable inspection technique. Although the ultrasonic pulse-echo technique is the most simple and reliable inspection technique—allowing inspection of very small regions underneath a contact ultrasonic transducer in one measurement—it requires a significant amount of time to inspect large structures entirely. On the other hand, guided wave inspection has attracted attention because guided waves can propagate over a long distance along elongated structures. Relative to this, many studies have been published on the efficient inspection of pipes and railway tracks[4–6]. However, for a guided wave to travel over long distances, it is necessary to use a low frequency range below approximately 50 kHz, which sometimes prevent detection of echo signals from defects of a desired size. Specifically, the use of guided wave inspection presents a dilemma between long-range inspection and detection of small defects[7,8].

Hayashi *et al.* has been developing defect imaging for plate-like structures using a scanning laser source (SLS) technique to solve the problems associated with ultrasonic pulse echo technique and guided wave inspection[9–13]. In defect imaging using the SLS technique, flexural vibration is generated by pulse laser irradiation, and the laser source is rastered over an inspected area. Then, the amplitude or frequency spectrum peaks are plotted in a two-dimensional map, generating an image of defects on the back surface of the rastering area. This imaging technique uses the characteristic of flexural vibration excited by laser irradiation, which is equivalent with a fundamental anti-symmetric (A_0) mode of Lamb waves in a very low frequency-thickness product range. When a laser for generating flexural vibration is located at a thinner area or in the vicinity of a defect, larger energy of flexural vibration is generated at the laser source, which results in larger amplitude of waveform or larger frequency spectrum peak at a defected area. This is discussed in Refs. 6) and 12) thorough theoretical and experimental results.

In previous studies, using a range of low frequency waves below 20 kHz, images of notch-type defects approximately 2 mm wide were generated, demonstrating that the defect imaging technique with SLS works and is effective even in such a low frequency range. Therefore, this imaging technique can utilize new receiving devices such as acoustic microphone, piezo-electric vibration disk, laser Doppler vibrometer (LDV), and 40-kHz air-coupled ultrasonic sensor, all of which have not been used for ultrasonic inspection. Although a piezo-electric vibration disk adhered to the inspection object can detect vibrations with high sensitivity, this contact technique imposes restrictions on practical use. On the other hand, the use of LDV enables inspection of plate-like structures from a remote distance[11], leading to its wider application in large structures. However, because LDV requires a sufficient intensity of reflected or scattered beams from an inspected object to effect stable measurement of vibrations, it is at times difficult to measure vibrations generated by an object with rough surfaces and large fluctuations as those found in outdoor structures or inclined surfaces as pipes. Moreover, considering simultaneous detection at multiple points using multiple devices, the LDV requires a high initial cost and it takes time to align multiple laser beams before measurements. A 40-kHz air-coupled ultrasonic sensor, usually used in distance measurement, is also one of the promising receiving devises for the imaging technique[13]. However, it shows very narrowband characteristic at 40 kHz, which limits the applications of the imaging technique. For

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example, the previous studies showed that defect images by this technique can be improved by using multiple frequencies even with a single or small numbers of receiving points, which was called frequency image averaging (FIA) in Ref. 10). However, a narrowband air-coupled sensor would prevent the use of FIA.

Accordingly, in this study, silicon acoustic microphones are introduced as receiving devices to solve the issues described above. First, the effect of the distance between the aluminum alloy plate and silicon microphone on the generation of defect images is investigated. Then, considering that acoustic data below approximately 20 kHz are used in the imaging experiments, a wireless microphone unit equipped with a battery-driven microphone, amplifier, and Bluetooth audio transmitter is developed. In addition, the applicability of the wireless system to remote measurements is discussed.

2. Experimental System and Plate Specimen

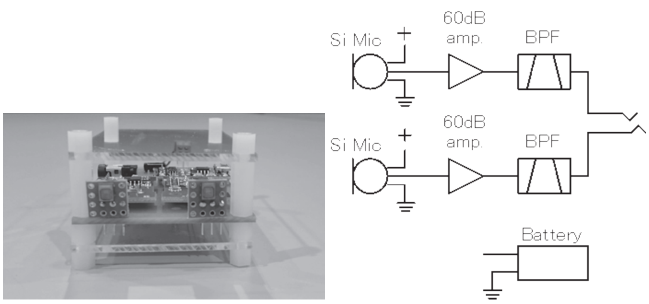
Figure 1 shows the system and plate specimen used in the experiments. Fiber laser equipment (Fujikura FLC-0300S) was used for generating elastic waves in the plate. A continuous wave laser having a wavelength of 1096 nm was modulated by external signals, and the modulated laser beam generated narrowband burst elastic waves. In the experiments described below, narrowband burst waves in the range of 10–14 kHz were generated by providing rectangular modulation signals, similar to the procedure used in the previous study[10].

Figures 2 (a) and (b) show an image and a function diagram of the developed microphone unit, respectively. Ultrasonic silicon microphones (Knowles Acoustics, SPM0404UD5) with a frequency range of 10–65 kHz were adopted as receiving devices. As shown in Fig. 2 (b), the microphone unit includes 60 dB amplifiers, band-pass filters, and battery to establish stand-alone reception without power cables. Directivity is negligible in audio range. Two microphones were installed in one unit because the acoustic data obtained by these microphones can be simultaneously transferred by Bluetooth stereo audio transmitter in the latter experiments. In the fundamental experiments, which are described in section 3, the sensor unit is connected to the analog-digital converter by a BNC cable, whereas wireless data transfer is used in the experiment described in section 4.

As shown in Fig. 1, an aluminum alloy plate measuring 500 mm × 500 mm × 3 mm with a notch-type defect forming the letter "K," 2 mm wide and 1.5 mm deep on the back surface, was used as the test specimen. The surface roughness is about $Ra = 0.31\ \mu$m in arithmetic average roughness. The laser emission area, corresponding to the imaging area, was 80 mm × 80 mm, encompassing the artificial defect. The microphone unit was located at a certain distance along the normal line from a point 50 mm from the right edge and 250 mm from the bottom edge on the plate surface. This test plate was cut halfway along its centerline to prove that defect images can be obtained even in a plate with a complex shape, based on Ref. 9).

3. Variation in Images Obtained at Varying Distances between the Microphone Unit and Plate

Defect images were obtained using the experimental system and test plate shown in the previous section. The output level of the fiber laser equipment was set to 100 W, which is one third of the maximum laser power, to avoid surface damage of the plate used in all the experiments described below. It must be noted that the actual laser output was lower than 100 W because of modulation. Following Ref. 10), the modulation signal consisted of rectangular waves having three frequency components—10, 12, and 14 kHz—connected in series and each having a duration of 3 ms. Elastic waves generated by laser irradiation travelled



(a) (b)

Fig. 2 Microphone unit developed. (a) Front view picture (b) Function diagram.

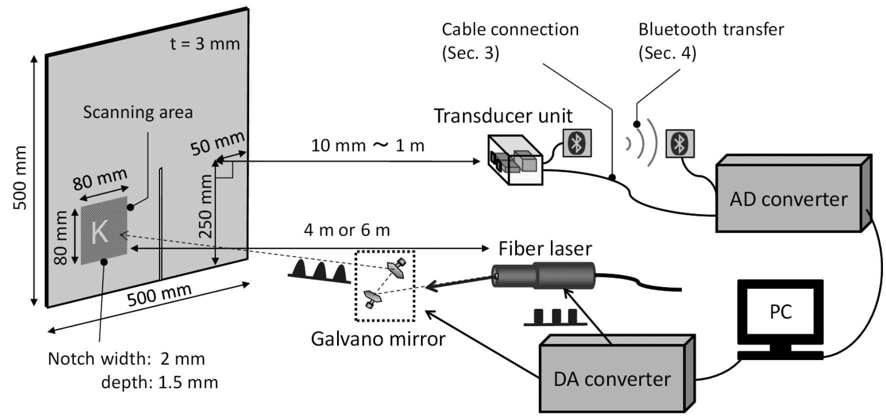


Fig. 1 Experimental system and plate specimen used in the experiments.

to and were scattered over the plate, leaked into the air, and caused vibrations that were detected by the silicon microphone. As shown in Fig. 1, imaging experiments were conducted for various distances between the microphone unit and plate surface. The detected signals were amplified at 60 dB by the built-in amplifiers, filtered by the built-in analog band-pass filter—having cutoff frequencies of 1.6 and 106 kHz— and digitized in the analog digital converter at a sampling frequency of 500 kHz. The digitized signals were filtered again by the digital band-pass filter having cutoff frequencies of 5 and 25 kHz. Frequency spectra were calculated from the recorded waveforms of 40 ms durations from the beginning of laser irradiation. Values appearing at 10, 12, and 14 kHz were averaged, and these values were used for generating the defect images. This procedure, called frequency image averaging, is discussed in detail in Ref. 10).

Figure 3 shows defect images obtained at various distances between the microphone unit and test plate. Values are plotted in gray scale, in which black is assigned a maximum value and white as zero. In these imaging experiments, signals from only one microphone were used. Defect shapes were obtained in darker dots in Figs. 3 (a)–(f), presenting that that laser irradiation at the area of notch-type defects provides larger vibration energy in the plate[12)]. Approximate trends that as the distances increase defect images become more unclear were observed, which occurs because of attenuation in air. In Fig. 3 (g), the defect image was not obtained at the set distance.

Based on the waveforms recorded in the experiment conducted for a distance of 1000 mm, signals with very large amplitude, totally different from those obtained at other distances, were observed. As bases for comparison, Figs. 4 (a) and (b) show the typical waveform and its frequency spectra, respectively, obtained at a distance of 1000 mm as well those obtained at 10 mm. Both waveforms are signals detected when a laser source is located at the left bottom corner of the image. Because frequency peaks at a distance of 1000 mm become much larger than those obtained at 10 mm, the frequency spectrum for the latter is magnified 20 times. Although distinct waves are not seen in Fig. 4 (a) corresponding to the distance of 10 mm, frequency peaks are observed clearly at 10, 12, and 14 kHz, as shown in Fig. 4(b). The large peak at 16 kHz obtained for the 10-mm distance is intrinsic noise originating from the experimental equipment, whereas a very clear waveform was obtained for the 1000-mm distance in the time range of 0–9 ms, corresponding to the laser irradiation interval. Because waveforms travelling in air would have delays, the signal appearing from 0 ms to 9 ms is not a sound wave, but a waveform generated by the photovoltaic effect or the small heat change in the microphone surface because of the laser beam scattered on the plate surface and reflected back to the microphone. Because these large waveforms obtained for the distance of 1000 mm do not contain information on the inner condition of the plate, the image in Fig. 3 (g) does not provide the defect image. Therefore, it can be concluded that the microphone unit must be located in an area that is not very far from the test plate and the scattered laser beam does

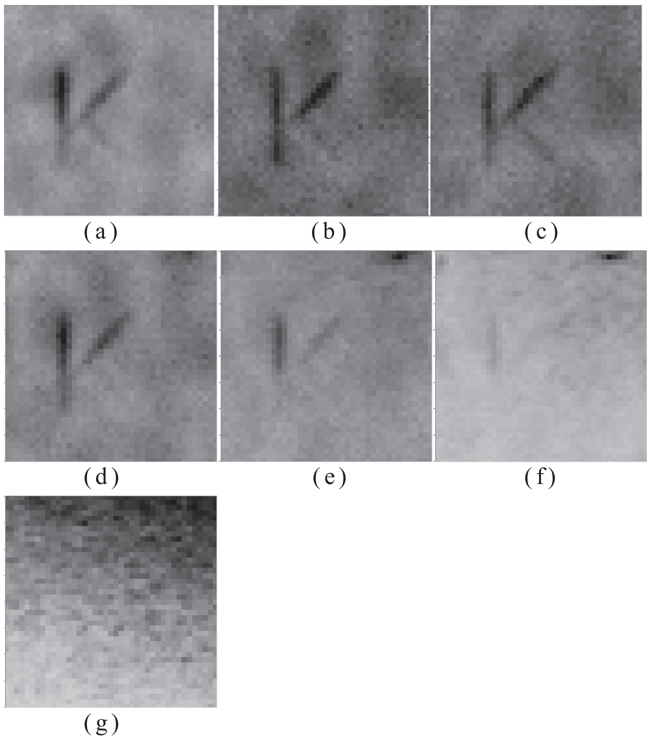


Fig. 3 Defect images obtained at various distances between the microphone unit and test plate. (a) 10 mm, (b) 100 mm, (c) 200 mm, (d) 300 mm, (e) 400 mm, (f) 500 mm(g) 1000 mm.

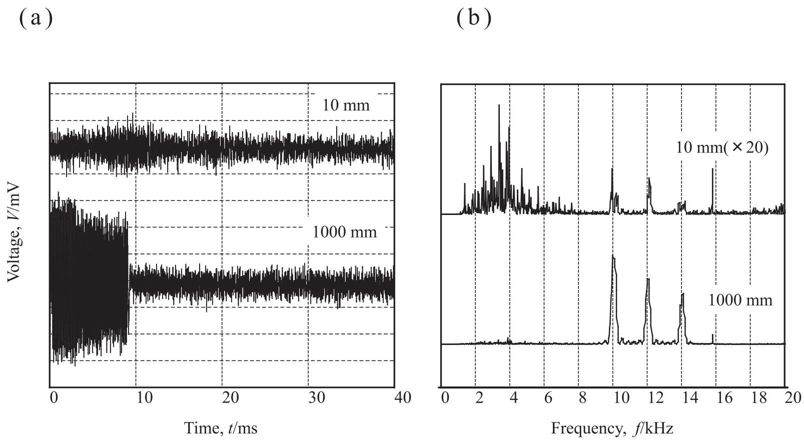


Fig. 4 Waveforms and frequency spectra for 10 mm and 1000 mm. (a) Waveforms, (b) Frequency spectra.

not reach it.

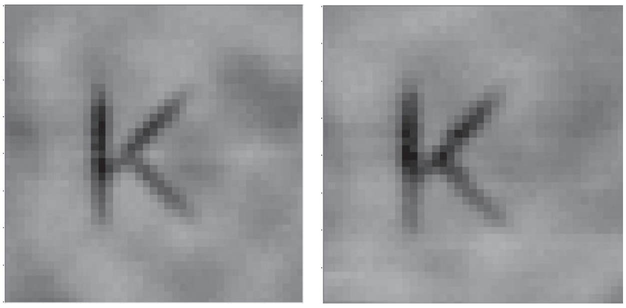
4. Remote Imaging Using Audio Transfer over Bluetooth

From the results described above, it was found that the microphone unit cannot be placed at long distances such as 5 m or 10 m. Moreover, long cables between the microphone unit and other measurement equipment prevent practical inspection of large structures. Focusing on the fact that the imaging experiments used audio data below approximately 20 kHz, experiments on defect imaging were conducted by transferring the received signals through a wireless audio transmitter by Bluetooth (TaoTronics, TT-BA07). As described in the previous section, the distance between the laser equipment and test plate was approximately 4 m, and the microphone unit was placed 20 mm away from the plate. During Bluetooth data transfer, which requires digital data processing, a signal delay of approximately 190 ms was observed. Therefore, data acquisition started 190 ms after laser irradiation commenced. Furthermore, because the Bluetooth transmitter can transfer two sets of audio data simultaneously, two microphones were used. The other setups such as the modulation signal and frequency image averaging were the same as those described in the previous section. Figure 5 (a) shows the image obtained through the wireless transmission experiment. It can be observed that the artificial defect was appropriately visualized, demonstrating that remote measurement through the wireless system is effective.

Figure 5 (b) shows the result obtained at a distance of 6 m. Because 6 m is within the transmitting distance of the Bluetooth transmitter, almost the same result as that in Fig. 5 (a) was obtained. Although the laser spot might slightly expand as the distance increases, the diameter would be sufficiently small compared with the wavelength, and therefore, the image would not vary with distance.

5. Conclusions

Experiments on defect imaging were performed by generating narrowband burst waves ranging from 10–14 kHz with the SLS technique and by receiving leaky waves with a silicon microphone unit. The experiments showed that non-contact imaging of plate-like structures was possible using the experimental system. Moreover, the experimental results revealed that the silicon microphone unit must be placed at an area where it does not receive scattered laser beams and the leaky acoustic waves do not attenuate. Furthermore, when the microphone unit was connected to a Bluetooth audio transmitter, the receiver unit can be used independently, and



(a) (b)

Fig. 5 Generated defect images using wireless measurement. (a) 4 m, (b) 6 m.

a defect image could be generated from a distance of 6 m once the wireless small sensor unit was placed close to the inspected plate.

Because multiple transmitters can be used simultaneously, and frequency bandwidth and transmission distance are dramatically improving, the imaging technique presented above has potentials for wider applications.

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